

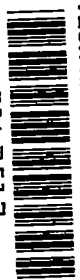
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RESEARCH MEMORANDUM

A REVIEW OF RECENT INFORMATION ON BOUNDARY-LAYER
TRANSITION AT SUPERSONIC SPEEDS

By Alvin Seiff

Ames Aeronautical Laboratory
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RESEARCH MEMORANDUM

A REVIEW OF RECENT INFORMATION ON BOUNDARY-LAYER

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SUMMARY

Several investigators have found that lowering the surface temperature of a smooth body increases the extent of the laminar boundary layer on it very sharply in some ranges of test conditions. This is consistent with the theory of laminar stability which predicts the existence of a region of complete stability to two-dimensional disturbances at Mach numbers between 1 and 9 when the wall temperature is lowered sufficiently. However, when surface roughness exceeds some critical amount, the favorable effects of low wall temperature may be counteracted and roughness can control the position of boundary-layer transition. Existing evidence indicates that this is the case both inside and outside the theoretical region of complete laminar stability. In recent small-scale free-flight tests within the theoretically stable region, it has been observed that laminar stability is improved by raising the Mach number at constant wall-temperature ratio. This increased stability is evidenced by increased Reynolds number of transition on a given surface, and an increase in the permissible roughness height as Mach number is increased.

Angle of attack is a cause of transition on the sheltered sides of slender bodies of revolution. If this is interpreted as being due solely to the pressure-rise coefficient encountered by streamlines on the sheltered side, it appears from one investigation that the critical pressure-rise coefficient is relatively insensitive to Mach number. Tests are required to define angle-of-attack effects on configurations other than slender bodies of revolution.

Blunting the leading edges of slender models has been experimentally found to increase significantly the extent of the laminar boundary layer. This is attributed to the reduction in the local Reynolds number at the boundary-layer edge in the presence of a blunt leading edge and its attendant strong shock wave. On low-fineness-ratio high-drag bodies of revolution, however, available data show boundary-layer transition Reynolds numbers which are low compared to those on slender models with comparable surfaces in flight at the same free-stream conditions. The low fineness

ratio reduces the ratio of wall to boundary-layer-edge temperature, which should be favorable, but appreciably reduces boundary-layer thickness and therefore accentuates roughness effects. Other changes, such as the reduced Mach number at the boundary-layer edge, may also be significant.

INTRODUCTION

Numerous authors (see, for example, refs. 1 and 2) have discussed the desirability of maintaining laminar boundary layers to the maximum possible extent on supersonic airplanes and ballistic missiles. The benefits to be derived thereby are two: significantly reduced aerodynamic heating and improved aerodynamic efficiency. There has therefore been considerable research recently devoted to the study of factors affecting boundary-layer transition at supersonic speeds. This research is aimed, in general, at defining the relationships between the extent of laminar flow and such variables as surface smoothness, wall temperature, pressure gradient, and Mach number. The purpose of this paper is to review briefly results that have been obtained from this research.

SYMBOLS

h	roughness height, in.
M	Mach number
$\frac{\Delta p}{p_0}$	pressure-rise coefficient
R_T	transition Reynolds number based on free-stream conditions
R_x	Reynolds number based on free-stream properties and axial distance from the leading edge
R_l	length Reynolds number based on free-stream properties
$(R_1)_B$	local Reynolds number outside the boundary layer of a blunted body
$(R_1)_S$	local Reynolds number outside the boundary layer of a pointed body
T_r	laminar recovery temperature, $^{\circ}R$
T_w	body-surface temperature, $^{\circ}R$

T_1 boundary-layer-edge temperature, $^{\circ}\text{R}$
 δ laminar boundary-layer thickness, in.
 θ_c cone half-angle, deg

Subscripts

o free stream
 1 boundary-layer edge
 c cone
 p flat plate

DISCUSSION

Effect of Wall Temperature Ratio

Over the past several years, a number of investigators have studied the effect of body surface temperature on transition, both theoretically and experimentally. Theoretically, according to Lees and Lin (ref. 3), lowering the body surface temperature improves the stability of the laminar boundary layer - the minimum Reynolds number at which two-dimensional disturbances undergo amplification is increased. To determine whether this improved stability is realized experimentally, several supersonic wind-tunnel tests have been conducted in recent years, and it is now well established that lowering the wall temperature generally increases the extent of a laminar boundary layer. Two sets of wind-tunnel data which show this, references 4 and 5, are reproduced in figure 1. There are also some new flight data available which extend the range of these data to lower wall temperature ratios and higher Reynolds numbers. These data were obtained using relatively large rocket-driven models, either air launched (ref. 6) or ground launched (unpublished data from the Langley PARD). From certain portions of these flights, data for constant or nearly constant Mach number with appreciable variation in wall temperature can be extracted and such data are included in figure 1. The points with arrows indicate that transition occurred ahead of the instrumented portion of the model (arrow down) or beyond the instrumented portion (arrow up). The data of reference 6 support the wind-tunnel data, particularly when the directions of the arrows are considered. The lower set of PARD data also fit the general trend, but indicate that under some conditions, the strongly favorable effect of lowering the wall temperature may level off. The upper set of PARD data show an unfavorable effect of lowering the wall temperature. However, it is very difficult in these

tests to hold all variables constant except one. In this particular case, length Reynolds number varied simultaneously with wall temperature. The effects of the two variables may then be mixed in producing the result shown.

The theory of Lees and Lin (ref. 3), in addition to predicting the favorable effect of lowering the wall temperature, further predicts that reducing the wall temperature below certain critical values which are a function of Mach number will produce complete laminar stability, such that small two-dimensional disturbances of all frequencies are damped at all Reynolds numbers. The wall-temperature limits of the completely stable region of this type calculated by Van Driest (ref. 7) from the theory of Lees and Lin are shown in figure 2 and compared with the temperature conditions of recent tests which entered the theoretically stable region. This region had sometimes been hopefully regarded as a region in which transition would not occur, but it has been conclusively shown by the tests at the conditions indicated in figure 2 (and the earlier data of ref. 8) that transition will occur in the region of complete stability in response to surface roughness and other causes. In this connection, it should be noted that Dunn and Lin (ref. 9) have analyzed the case of three-dimensional disturbances and found that the laminar "boundary layer can never be completely stabilized with respect to all three-dimensional disturbances." According to this theory, then, for three-dimensional disturbances, no counterpart to the fully stable region of figure 2 exists. This does not detract, however, from the observed advantages (fig. 1) of low wall temperature for purposes of maintaining laminar boundary layer.

Effect of Mach Number

In order to investigate the effect of Mach number on transition at constant low values of the wall temperature ratio, tests have recently been made in the Ames supersonic free-flight wind tunnel. The Mach numbers and wall temperature ratios covered are indicated in figure 2 by the diamond symbols. The models employed are shown in figure 3. Previous experience had indicated that on very smooth surfaces transition would be far back on the models at all Mach numbers so that no observations of the effects of Mach number could be made. It was necessary, therefore, to use rough surfaces to bring transition forward, and for reasons of reproducibility, fine-threaded surfaces of the type shown in the microphotograph were selected. The location of transition was measured from shadowgraphs as described in reference 8. The results of tests conducted by R. J. Carros with the ogive-cylinder models, are shown in figure 4. Increasing the Mach number had a pronounced favorable effect on the extent of laminar flow over a given surface, particularly when certain critical combinations of Mach number and thread height were reached. After a sharp increase, transition Reynolds number appeared to

level off at stations near the base of the model, but this was not conclusively shown since some cases of fully laminar flow up to the fins were recorded in this region. These are indicated by the points with arrows as being beyond the range of observation. In figure 5, two of the shadowgraph pictures obtained are reproduced to show directly the change in the boundary layer associated with raising the Mach number from 1.87 to 3.40 on a 0.0004-inch threaded surface.

In order to investigate the effect of the type of roughness on this result, a series of smooth models were sandblasted with fine grit to produce the roughness described at the right side of figure 4. The trend observed with these models is shown by the inverted filled triangles to be similar to that found with the threaded surfaces. It is interesting that the sandblasted surface, with roughness height generally less than $1/3$ that of the roughest thread, nevertheless had lower transition Reynolds numbers at all observed test Mach numbers which suggests that a threaded (two-dimensionally) roughened surface is superior to a bumpy (three-dimensionally) roughened surface.

The flight data of figure 2 can be examined for the effect of Mach number at constant wall temperature ratio on relatively smooth bodies. Results obtained are shown in figure 6 and compared with the data of figure 4. At Mach numbers above 2, the highly polished flight models seem to show trends similar to those from the tests with the roughened small-scale models. However, the data of Rabb and Disher (ref. 6), when laminar, were actually fully laminar with transition beyond the range of the measurements. Thus, no definite information on effect of Mach number is contained in the two points shown. The flight data of the Langley Pilotless Aircraft Research Division are similar to the small-scale test data at Mach numbers above 2. At lower Mach numbers, an opposite trend is shown. Whether this can be explained in terms of the length Reynolds number variations present in the flight tests, or whether there is really a reversal in this region, is not yet established.

Cross plots of the data shown in figure 4 together with data from tests with the contoured tubes can be made to define the effect of roughness height on transition Reynolds number at several fixed Mach numbers. For generality, it was desired to relate the roughness height h to the laminar boundary-layer thickness δ . For surfaces of constant roughness height at all stations, however, the ratio of roughness height to boundary-layer thickness varies with axial position on the model. Therefore, a parameter to represent the relationship of roughness height to boundary-layer thickness over the entire surface was sought. Examination of the equations for h/δ as a function of the Reynolds number based on axial distance from the leading edge R_x showed that a dimensionless group

$\frac{h}{\delta} \sqrt{R_x}$ was constant over the surface of a flat plate with constant roughness height and a given Reynolds number per foot, and would therefore

specify the relation of roughness to boundary-layer thickness for all points on the surface. Accordingly, this was the roughness parameter used. In figure 7, comparison of the ogive-cylinder data and the contoured-tube data on the basis of this parameter is shown for a Mach number of 4.9 and a wall temperature ratio of 1.8. The two models differed in boundary-layer growth rates because of shape and because of Reynolds number differences, 27 million per foot for the ogive-cylinder and 36 million per foot for the contoured tube. The pressure and Mach number distributions on the nose sections were, however, nearly identical by design. The correlation shown in the figure was realized only when the boundary-layer-growth equations for the nose sections of the bodies were used rather than those for the cylindrical sections. This implies that the observed roughness effects are predominantly controlled by the flow on the body nose.

The effect of the roughness parameter on transition at other Mach numbers is shown in figure 8 and is compared with the curve for a Mach number of 4.9. The wall temperature ratios for the free-flight wind-tunnel curves are 1.8 at the two higher Mach numbers and 1.0 at $M = 3.5$. Examination of the upper two curves indicates that increasing the Mach number at constant wall temperature ratio increased the maximum extent of laminar flow over threaded surfaces and also increased the permissible roughness. The curve for $M = 7$ is characterized by insensitivity to roughness height up to a critical roughness height, followed by an abrupt forward movement of transition.

Data for roughness parameters below 60 have been obtained from several wind-tunnel and flight tests. Three points from these tests are included on the figure. They show that at very low values of the roughness parameter, of the order of 10, and at low values of the wall-temperature ratio, very substantial laminar runs are realized. These observations tend to support the early data of Sternberg (ref. 10), who found a transition Reynolds number greater than 57 million from the flight test of a polished cone at a roughness parameter of 17 and a wall-temperature ratio of 1.2.

Effect of Angle of Attack

The above considerations have been limited to the case of zero angle of attack. Experiments have shown that when slender bodies of revolution are smooth enough so that roughness does not cause transition, transition due to angle of attack can occur on the sheltered side at angles of attack above certain critical values. It has been suggested (ref. 8) that this results from the pressure rise encountered by streamlines flowing over the sheltered side, due partly to the axial pressure distribution and partly to the cross-flow pressure distribution. This reasoning leads to the expectation that the critical angle of attack will depend, among

other things, on the pressure distribution at zero angle of attack. If the axial-pressure-rise coefficient is too great, pressure-rise transition would be expected to occur at zero angle of attack. Mach number also should influence sheltered-side transition through its effect on the pressure distributions, and through its effect on the critical pressure-rise coefficient. An effect of Mach number on sheltered-side transition was observed in tests in the supersonic free-flight wind tunnel with the ogive-cylinder model of figure 3. The critical angle of attack appeared to decrease with increasing Mach number. When analyzed by the method of reference 8 to determine the pressure-rise coefficient at the transition point, these observations led to the data of figure 9, where critical pressure-rise coefficient is plotted as a function of Mach number. The critical pressure-rise coefficients in the form $\Delta p/p_0$ (where p_0 is the static pressure in the free stream) are relatively independent of Mach number. Additional cases, references 11, 12, and 13, in which transition was apparently caused by pressure rise at zero angle of attack, on cone-cylinders and other models, have been collected by Carros and are included in the figure, and they tend to support the tentative conclusion that at supersonic speeds, the critical pressure-rise coefficient is independent of Mach number and wall temperature ratio. It will be desirable to test this finding by comparison with additional experiments. In all probability, further work will show at least a small dependence of critical pressure-rise coefficient on Reynolds number and on pressure distribution. The implication of figure 9 for bodies of low fineness ratio, and in particular, bodies with continually favorable pressure gradient, is that such bodies should be free of sheltered-side transition in the low angle-of-attack range. However, it has not been demonstrated that the pressure-rise effect is the only effect which can influence sheltered-side transition, and additional experiments are required to investigate the case of low-fineness-ratio bodies.

Effects of Low Fineness Ratio and Tip Bluntness

At high supersonic speeds, it seems necessary to use round-nosed bodies and wings with blunt leading edges because of aerodynamic heating. Similarly, low-fineness-ratio bodies have certain advantages over slender bodies for high-speed re-entry into the earth's atmosphere (ref. 1). It is therefore important to consider the effects of nose bluntness and low-fineness-ratio on boundary-layer transition.

Recently, Brinich (ref. 14) has made tests to determine the effect of leading-edge thickness on transition on hollow tubes at a free-stream Mach number of 3.1. His data are shown in figure 10(a). As leading-edge thickness was increased, transition Reynolds number increased to the maximum values shown for the 0.008-inch leading edge. Tests with a much thicker leading edge did not change the transition point significantly

from its position with the 0.008-inch leading edge. These data prompted Moeckel (ref. 15) to examine the effect of blunting on surface Reynolds number, since with a blunt leading edge, the air at the surface of the cylinder will have passed through a normal shock wave and will be altered in density, velocity, and temperature from the corresponding values with a sharp leading edge. This effect of the normal shock wave on the surface Reynolds number at a station far downstream of the bluntness was also noted by Dorrance and Romig (ref. 16) and is shown in figure 11, as a function of free-stream Mach number, for a relatively slender cone and a low-fineness-ratio cone. In both cases, the surface Reynolds number of the cones when blunt is a small fraction of the surface Reynolds number when sharp, particularly for the more slender cone. It should be noted, however, that, except for the bluntest cones at very high Mach number, the surface Reynolds number when sharp will fall well above the free-stream Reynolds number, so that the surface Reynolds number for blunt, low-fineness-ratio cones will not be reduced too far below free-stream values. Moeckel was able to explain the data of Brinich on the basis of these Reynolds number changes.

As an independent check on the data of Brinich, tests have very recently been conducted in the Ames supersonic free-flight wind tunnel by C. S. James, again using a tubular model with zero pressure gradient. The results are shown in figure 10(b). When the blunt leading edge was square cornered and normal to the air stream, the effect of increasing bluntness was adverse, as shown. It was suspected that this was due to detachment of the flow in turning the sharp corner, with the consequent formation of a separated bubble (possibly turbulent) and a reattachment shock wave. Therefore, a rounded leading edge of the same thickness was tried and this increased the extent of the laminar boundary layer appreciably, as compared to both the sharp leading edge and the square, thick leading edge. Thus, it appears that leading-edge shape is significant as well as leading-edge thickness.

In addition to the favorable effect of blunting on the local surface Reynolds numbers, there are some additional effects, in this case, unfavorable, associated with low fineness ratio; these are shown in figure 12. On the left the local surface Mach numbers are plotted as a function of cone angle for free-stream Mach numbers of 4, 8, and 20. The local Mach numbers on the cones of 30° half angle and greater are reduced to low supersonic values, almost independent of the free-stream Mach number. Blunting the cones further reduces the local Mach numbers to values indicated by the dashed curves. In view of the results for effect of Mach number on transition, it is conceivable that compression to low local Mach numbers will have a destabilizing effect on the laminar boundary layers.

In the right half of the figure, the effects on boundary-layer thickness of cone angle and tip blunting are shown. Boundary-layer thickness

on the cone is compared with that on a flat plate of equal length at identical free-stream conditions. The boundary-layer thickness on the cone differs from that on the flat plate as a result of several effects: the well known lateral spreading effect on the cones which reduces it by $\sqrt{3}$; the effect of the changed Mach number and air temperature at the boundary-layer edge; and the effect of the change in local surface Reynolds number. All these effects are included in the figure, which shows that the low-fineness-ratio cones have thin boundary layers relative to the corresponding flat plates. Increasing the Mach number reduces the relative thickness. Thin boundary layers would be expected to increase the tendency for roughness to cause transition. Slight blunting of the cones is therefore favorable in this sense, since the normal shock wave acts to make the boundary layer thicker than on corresponding sharp cones.

In figure 13, some preliminary data obtained by S. C. Sommer in the supersonic free-flight wind tunnel and by L. T. Chauvin at the Langley Pilotless Aircraft Research Division (filled circles) on transition on low-fineness-ratio bodies are shown. The bodies tested have included a 60° cone, 50° and 60° cones with spherical tips, a hemisphere, and a pointed ogive with steadily favorable pressure gradient. The transition regions observed are indicated by the vertical lines through the data points. The agreement between the data from the two facilities is remarkably good, and this may be only fortuitous in view of differences in the test Reynolds numbers. It has been apparent in these tests that the ease of obtaining laminar runs at Reynolds numbers of 10 million and greater which was experienced with the slender test models was not now present. A beneficial effect of increasing the Mach number is, however, shown as in the case of the slender models. The free-flight wind-tunnel models have been polished, in general, to a smoother condition than the corresponding slender models. To the eye, the models have appeared highly polished, with a gleaming, mirror-like surface. Microscopic examination, however, has indicated the presence of minute polishing scratches up to 10 microinches deep. It should also be noted that transition data from the shadowgraphs are not nearly so precise or definite with these models as with slender bodies, but it can usually be decided definitely whether the boundary layer coming off the model base is laminar or turbulent. It was, for example, almost invariably turbulent off the base of the blunted cone. The pointed 60° cone at $M = 8.25$ has given the longest laminar run to date, remaining laminar to a diameter behind the model base.

The difficulty in avoiding transition on these models is believed due to the thinning of the boundary layers and to the low surface Mach numbers. Additional work will be required to investigate these causes and to find the most favorable low-fineness-ratio shapes. It should be noted that the results of these tests may prove to be somewhat pessimistic because of the very high values of Reynolds number per foot

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employed, 18 million to 36 million. These high Reynolds numbers make the boundary layers very thin and increase the chances of roughness causing transition.

CONCLUDING REMARKS

From the preceding discussion, it would appear that on slender bodies with low surface temperature in flight at supersonic and hypersonic Mach numbers up to 7, it should be possible to maintain laminar boundary layers to Reynolds numbers of the order of 20 million. To do so, however, it will be necessary, even in the region of complete stability to two-dimensional disturbances given by theory, to avoid tripping the boundary layer by use of unduly rough surfaces or such other trips as angle-of-attack vanes on the body nose. One encouraging observation is that perfect smoothness is not required to maintain moderately long laminar runs if the roughness is of the two-dimensional threaded type described herein. With such surfaces, the permissible roughness increases with increasing Mach number. A favorable effect of increasing Mach number also seems to occur in tests with smooth surfaces, but further work will be required before this can be stated with assurance. The blunt leading edges required from the viewpoint of heating of the leading edge appear to be favorable in their effect on the extent of laminar flow on slender bodies.

Transition due to pressure rise along streamlines may prove to be more difficult to avoid than transition due to roughness. Pressure rise can occur as a result of angle of attack as well as configuration. Further investigation will be required to define the types of configuration which are most favorable in these respects.

When bodies of low fineness ratio are considered, several new effects are encountered. These include boundary layers considerably thinner than on slender bodies, strong favorable pressure gradients in some cases, and low Mach numbers at the boundary-layer edge. Experiments available to date show that the net effect of these factors is unfavorable - the transition Reynolds numbers observed have been generally below 10 million. Further study of this problem is necessary.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Nov. 3, 1955

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EFFECT OF BODY SURFACE TEMPERATURE ON TRANSITION

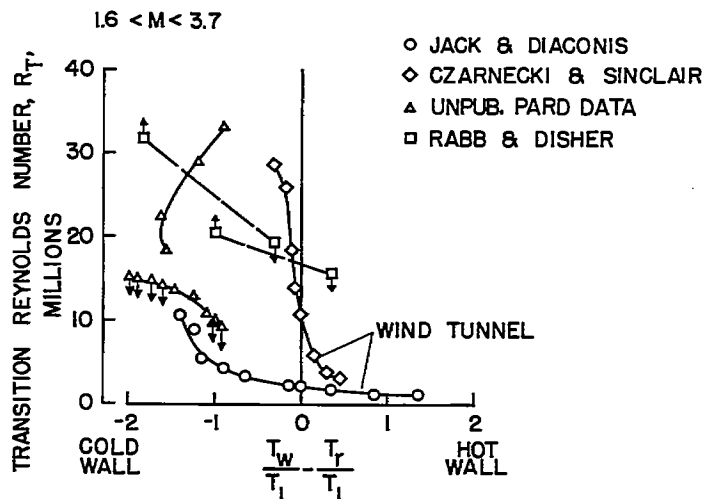


Figure 1

RECENT DATA WHICH ENTER THEORETICAL REGION OF LAMINAR STABILITY TO 2-DIMENSIONAL DISTURBANCES

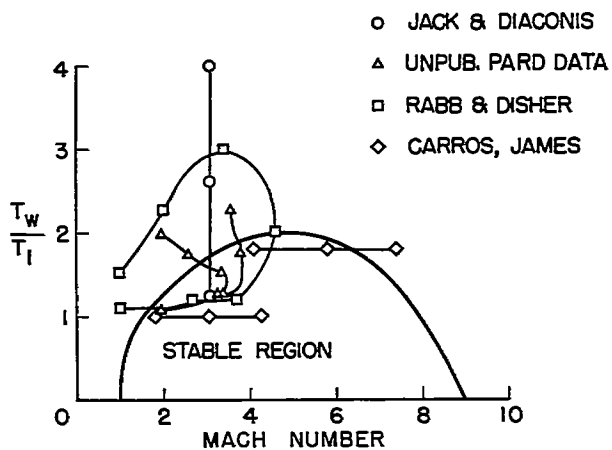


Figure 2

MODELS AND SURFACE FINISH USED IN FREE-FLIGHT TRANSITION EXPERIMENTS

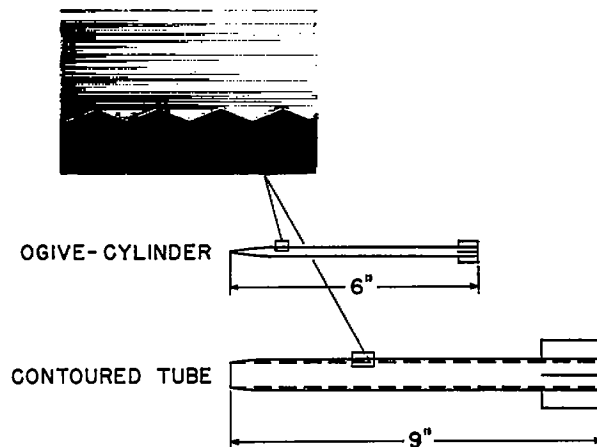


Figure 3

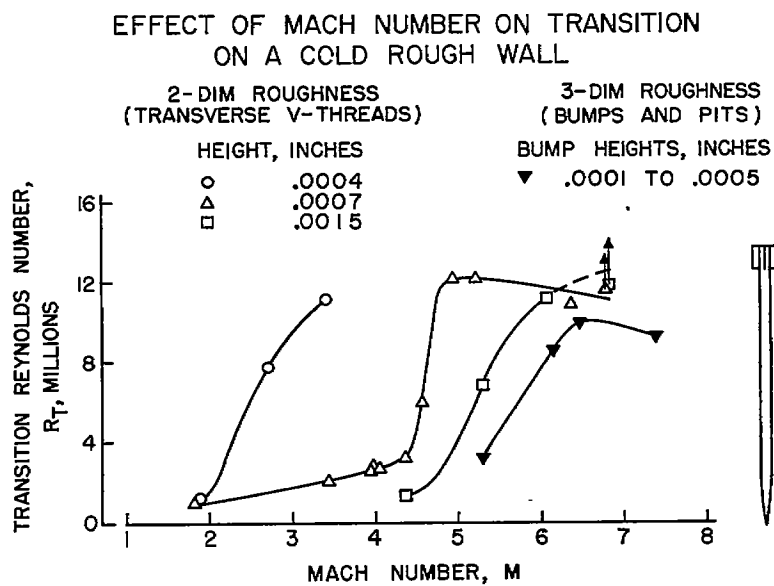
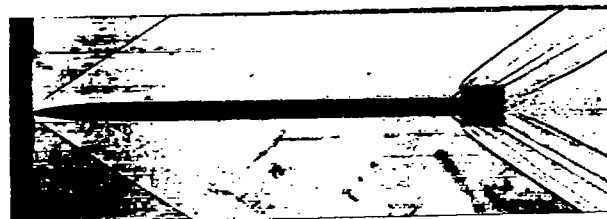


Figure 4

SHADOWGRAPHS OF TRANSITION ON A .0004-INCH THREADED SURFACE



$M=1.87, R_1=12.5 \times 10^6$



$M=3.40, R_1=13.1 \times 10^6$

Figure 5

MACH NUMBER EFFECT IN ROCKET-POWERED LARGE-SCALE FLIGHT TESTS

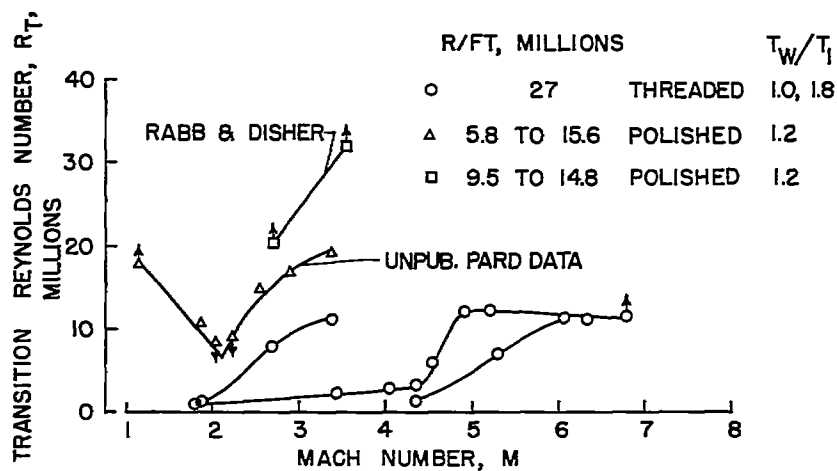


Figure 6

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CORRELATION OF DATA ON BASIS OF ROUGHNESS PARAMETER

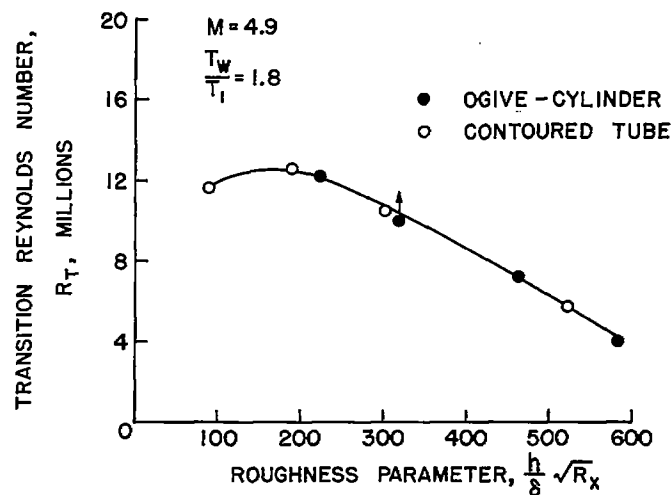


Figure 7

EFFECT OF ROUGHNESS PARAMETER ON TRANSITION

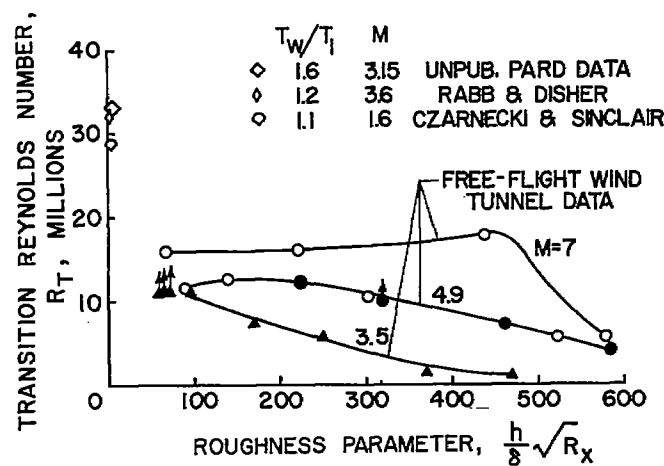


Figure 8

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COLLECTED DATA ON CRITICAL PRESSURE-RISE COEFFICIENT

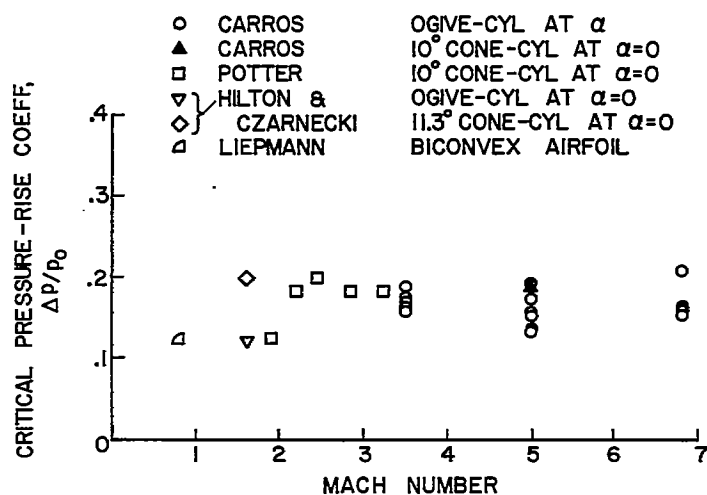


Figure 9

EFFECT OF LEADING-EDGE THICKNESS ON TRANSITION

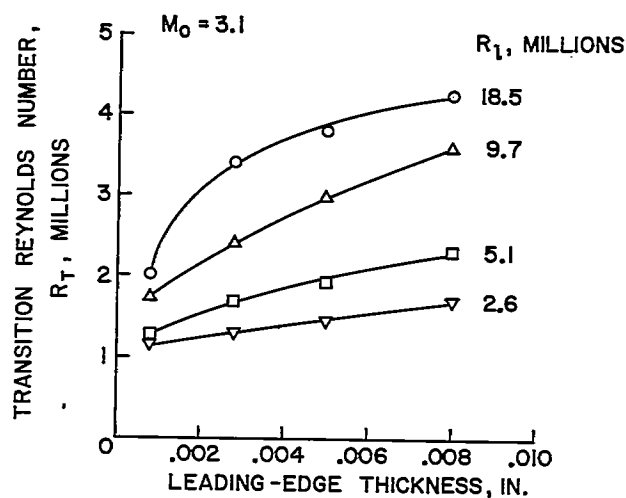


Figure 10(a)

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ADDITIONAL DATA ON LEADING-EDGE THICKNESS EFFECT

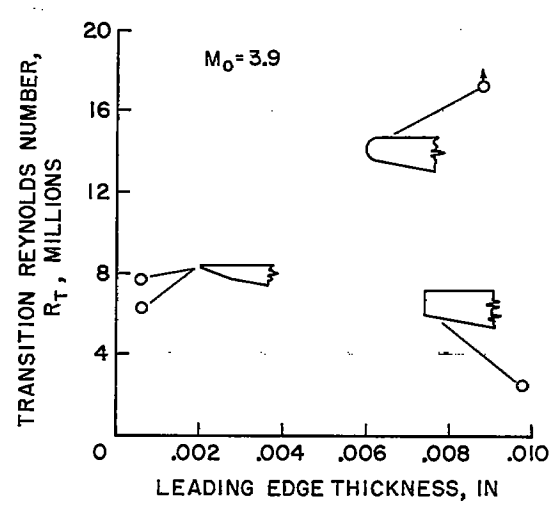


Figure 10(b)

EFFECT OF BLUNT NOSE ON LOCAL SURFACE REYNOLDS NUMBER

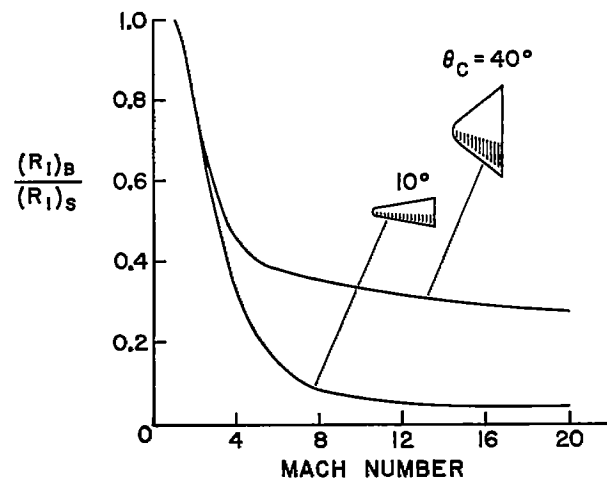


Figure 11

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EFFECTS OF CONE ANGLE AND TIP BLUNTING ON LOCAL MACH NUMBER AND BOUNDARY-LAYER THICKNESS

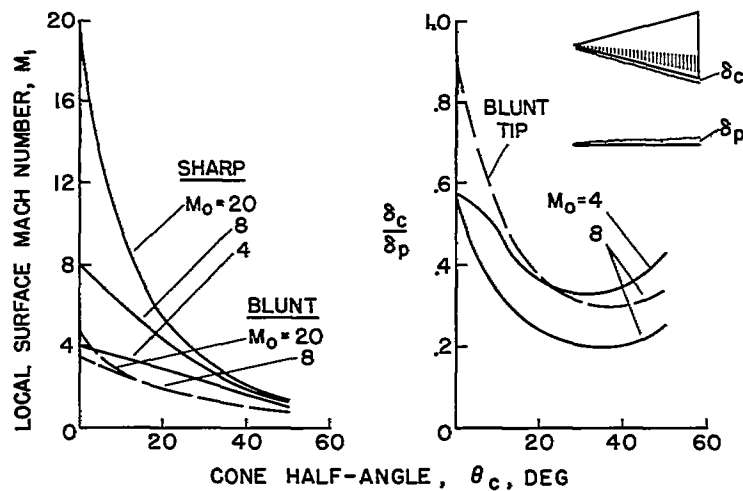


Figure 12

PRELIMINARY TRANSITION DATA FOR LOW FINENESS RATIO CONFIGURATIONS

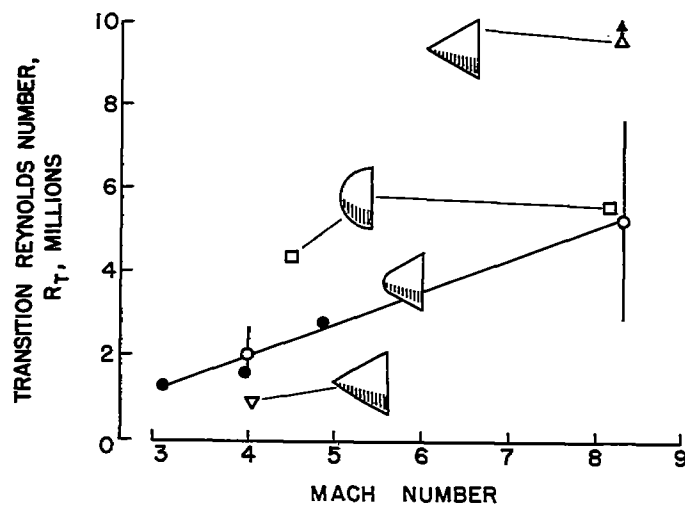


Figure 13